

Host silicon isotope effect on ^{31}P ENDOR

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August 25, 2009 Silicon QuBit Workshop, UC Berkeley

Supported by the Grant-in-Aid for Scientific Research #18001002
Special Coordination Funds for Promoting Science and Technology

Isotopically controlled silicon

Stable isotopes	Nuclear spin
^{28}Si 92.2%	$\rightarrow 0$
^{29}Si 4.7%	$\rightarrow \frac{1}{2}$
^{30}Si 3.1%	$\rightarrow 0$
^{31}P 100%	$\rightarrow \frac{1}{2}$

99.995% ^{28}Si

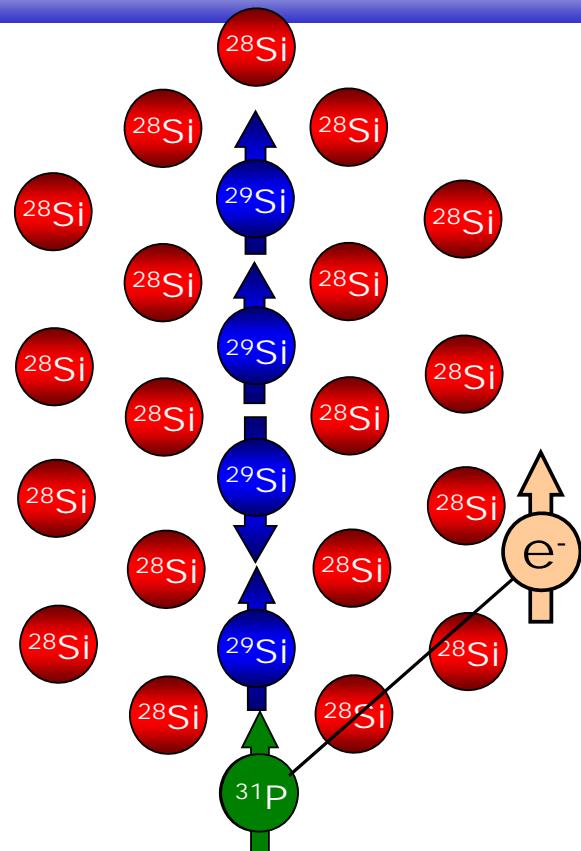


99.3% ^{29}Si

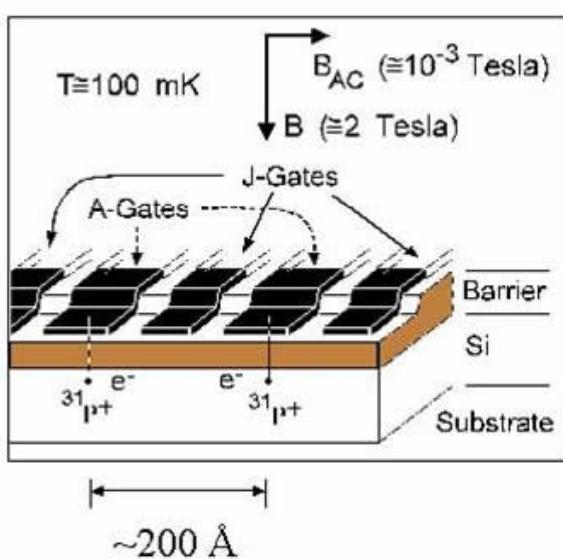


All-Silicon Quantum Computer

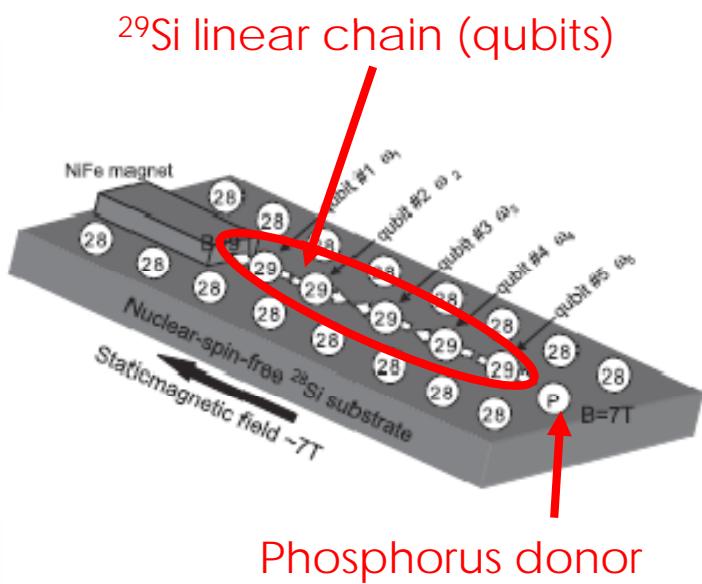
Phys. Rev. Lett. 89, 017901 (2002)



Phosphorus for quantum information processing



Si-based quantum computer
B. E. Kane, Nature, 393, 133 (1998)
Phosphorous nuclear and electron spin qubits



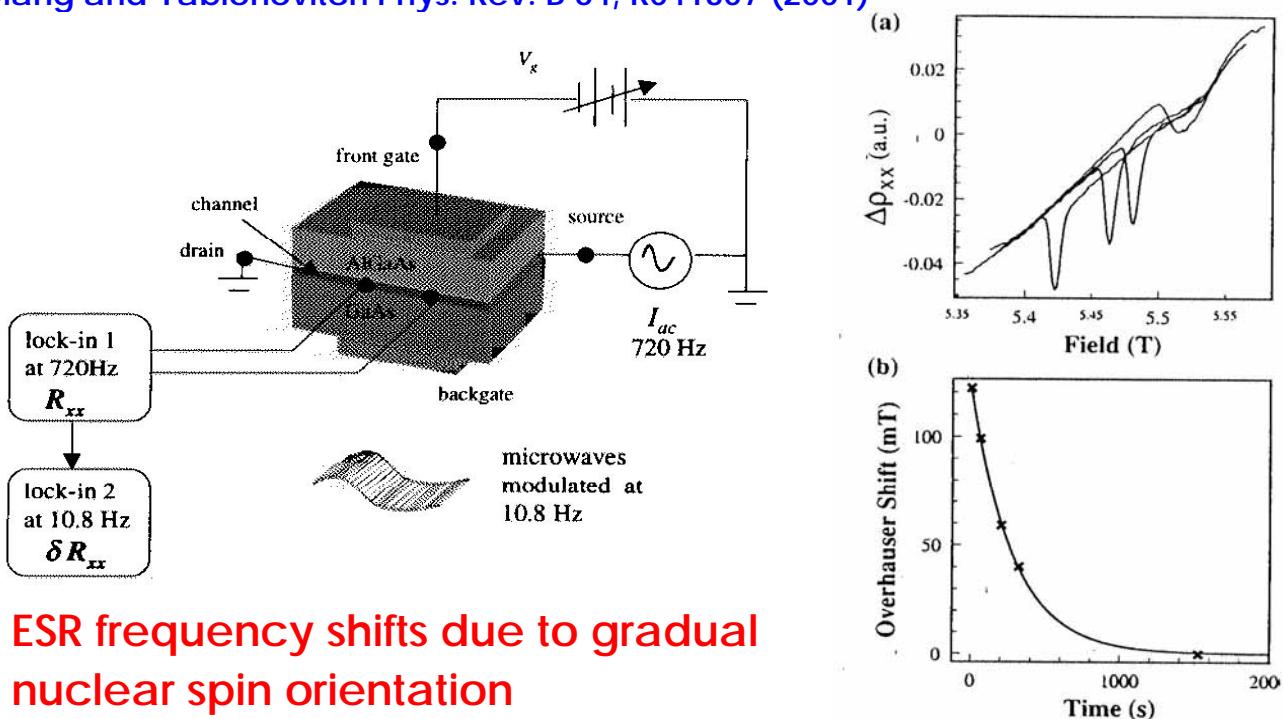
All-silicon quantum computer
T. D. Ladd et al, PRL, 89, 017901 (2002)
K. M. Itoh, Solid State Commun. 133, 747 (2005)
Phosphorous nuclear and electron spin qubits

Change in Si isotopic composition leads to change in ^{31}P NMR frequencies

Change in electron spin resonance frequency

Electrically detected electron spin resonance (ESR) of two dimensional electron gas (2DEG)

Jiang and Yablonovitch Phys. Rev. B 64, R041307 (2001)



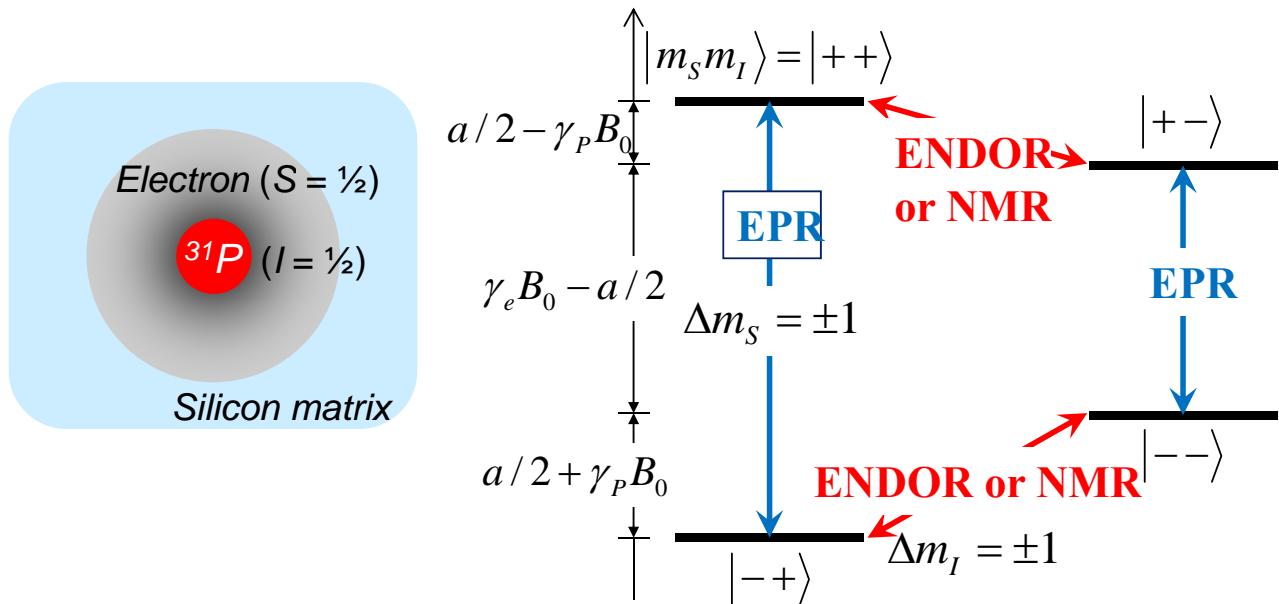
ESR frequency shifts due to gradual nuclear spin orientation

Phosphorus in Silicon

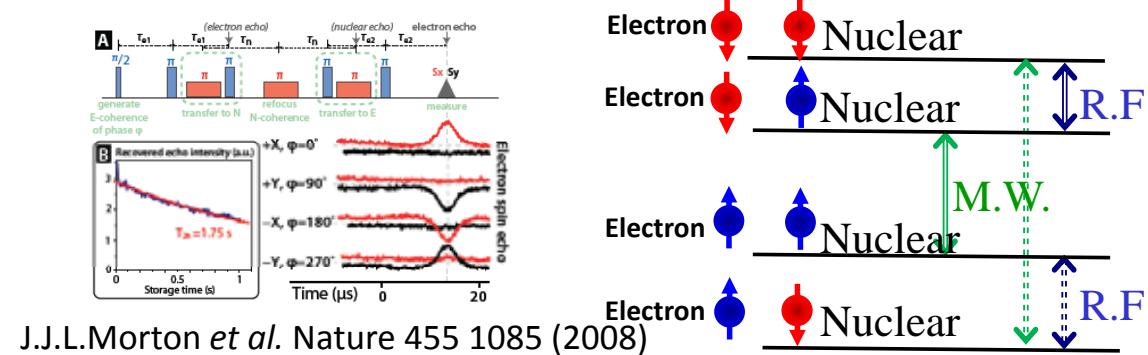
One of the most extensively studied donors in semiconductors

$$H_{e-P} \approx \gamma_e B_0 S_z + a S_z I_z - \gamma_P B_0 I_z \quad (m_s, m_I = \pm \frac{1}{2})$$

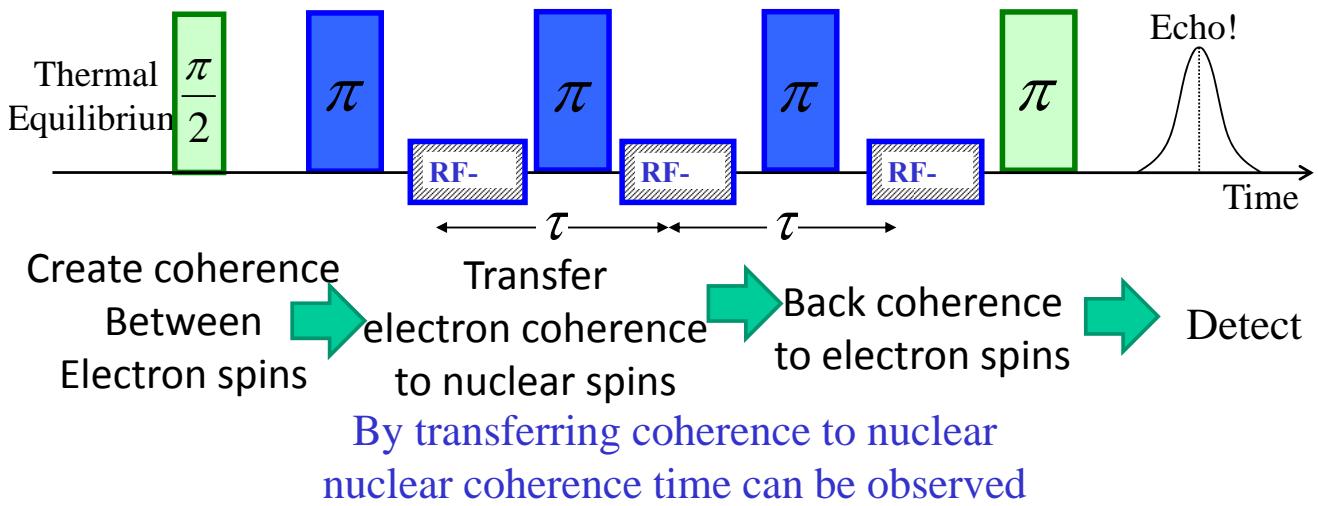
$$A = \frac{8\pi}{3} \gamma_e \gamma_P \hbar |\Psi(0)|^2$$



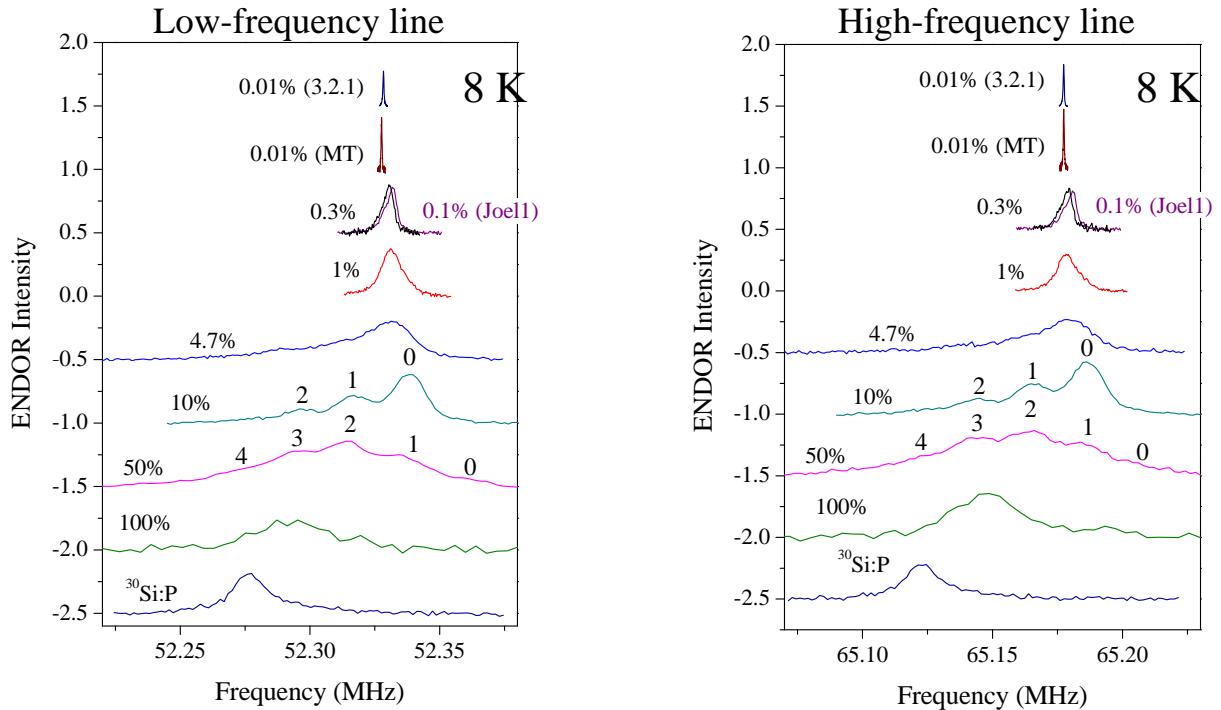
Pulse Sequence to probe ^{31}P



J.J.L.Morton et al. Nature 455 1085 (2008)

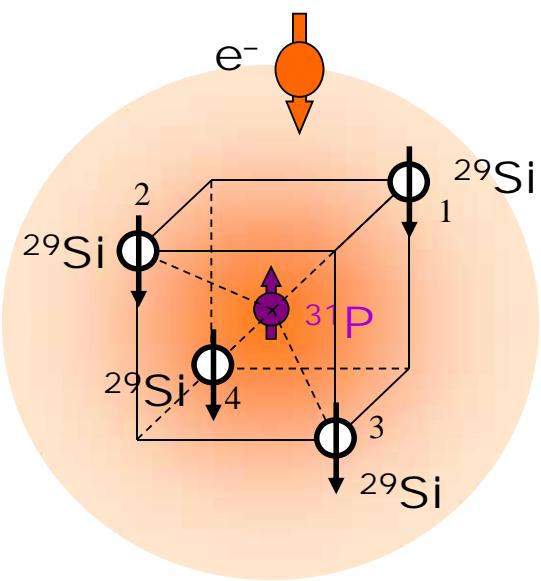
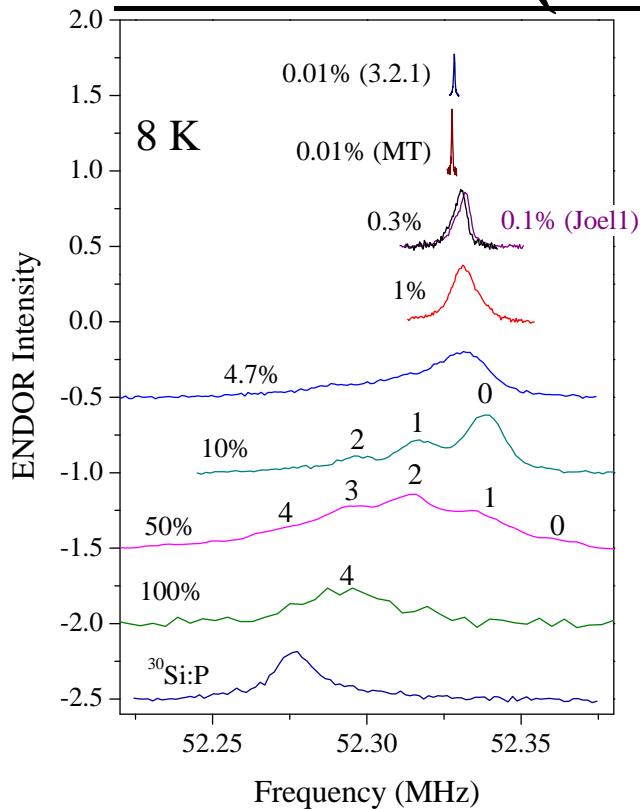


^{31}P ENDOR Spectra in Si



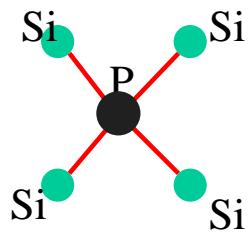
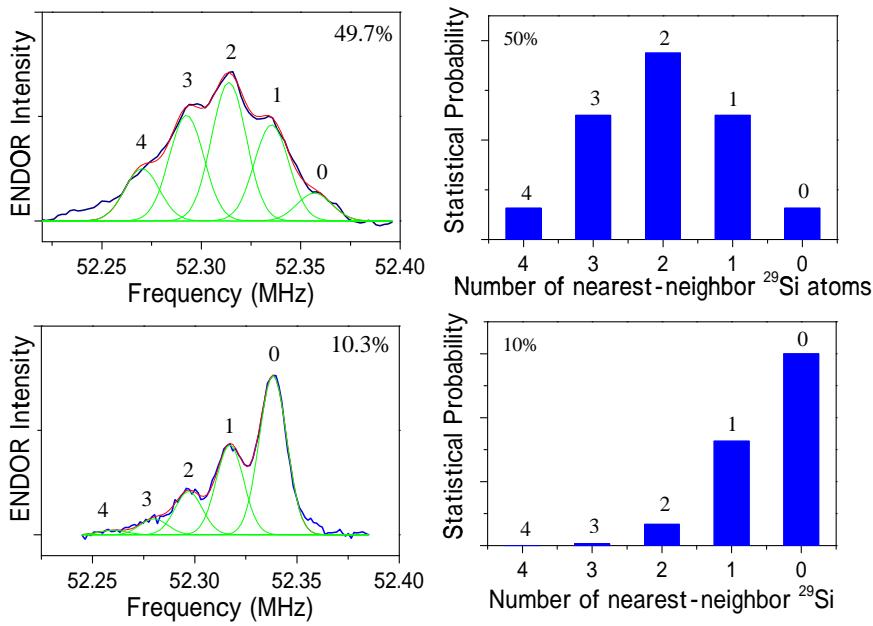
- Percentage labels on each spectrum indicate ^{29}Si content
- All samples contain about $10^{14-15} \text{ P/cm}^3$

^{31}P ENDOR(NMR) Spectra in Si



- Percentage labels on each spectrum indicate ^{29}Si content
- All samples contain about $10^{14-15} \text{ P/cm}^3$

ENDOR Fine Structure



Donor and four nearest-neighbor Si atoms

$$n_0 = (1-f)^4$$

$$n_1 = 4f(1-f)^3$$

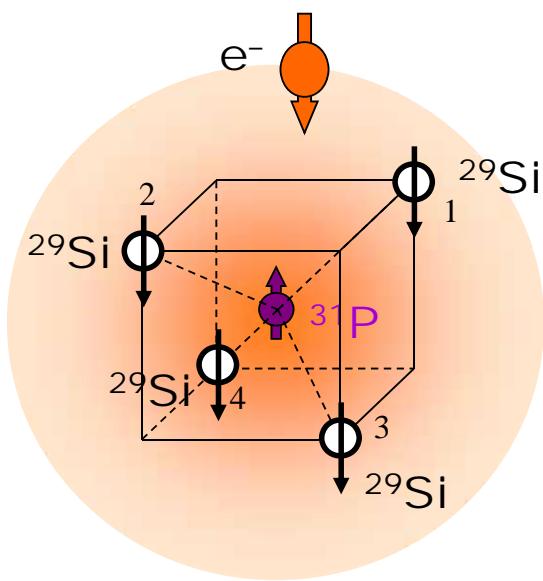
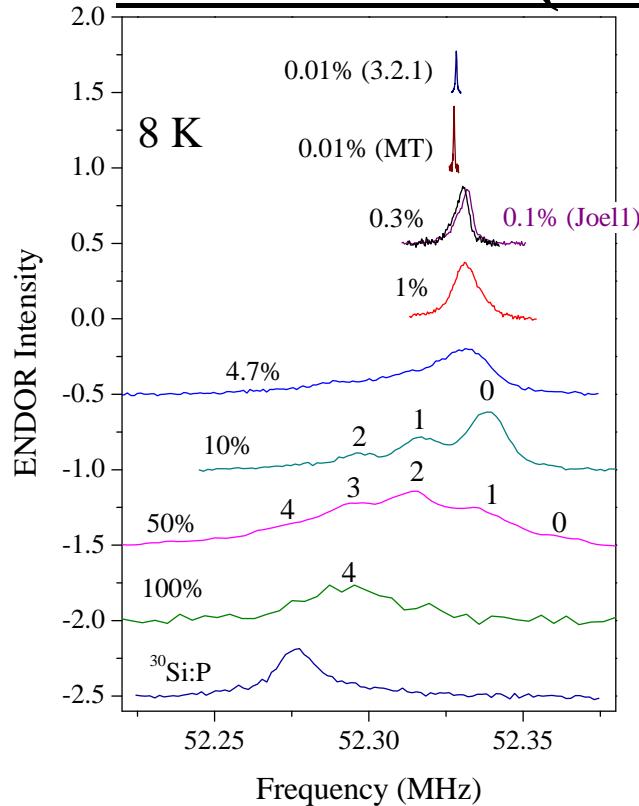
$$n_2 = 6f^2(1-f)^2$$

$$n_3 = 4f^3(1-f)$$

$$n_4 = f^4$$

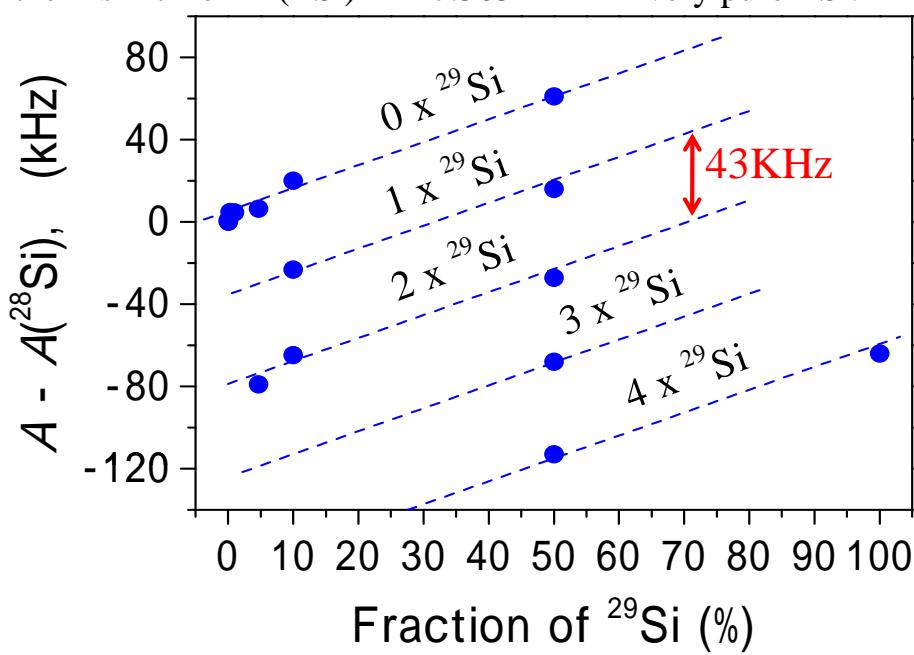
Statistical probabilities n_k for donor to have “ k ” nearest-neighbor ^{29}Si atoms
(f is a fraction of ^{29}Si)

^{31}P ENDOR(NMR) Spectra in Si



^{31}P ENDOR Signal Peak Shift

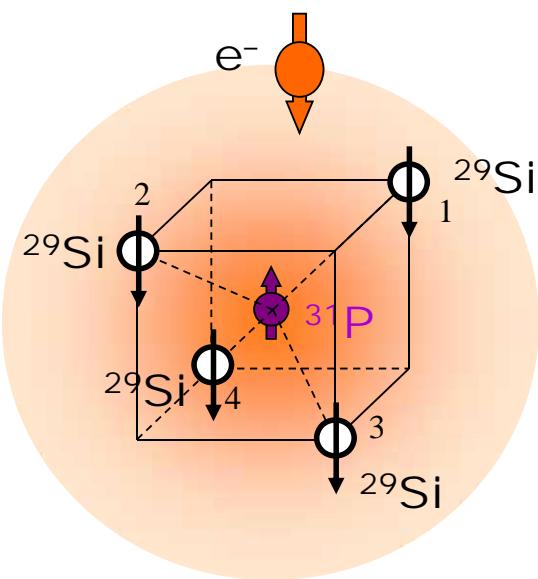
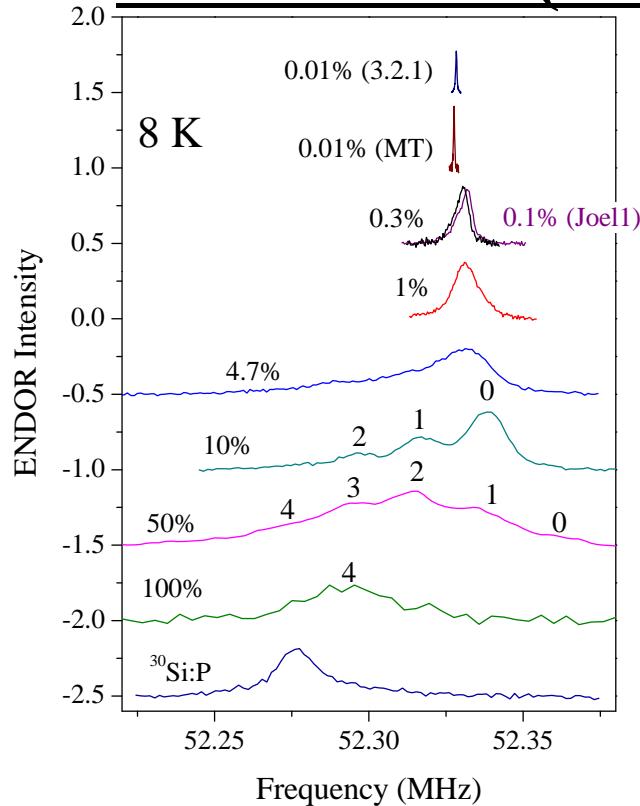
Plotted is the A shift from $A(^{28}\text{Si}) = 117.505 \text{ MHz}$ in very pure ^{28}Si .



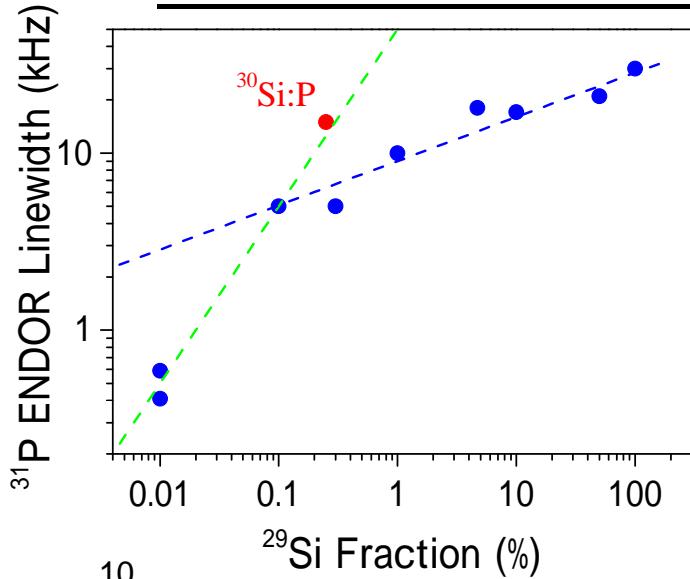
Number of nearest-neighbor are...

Constant : Hyperfine constant “A” increase with increasing fraction of ^{29}Si (dashed lines
Increased by one : “A” decreases by 43KHz (0.04% changes to A)

^{31}P ENDOR(NMR) Spectra in Si



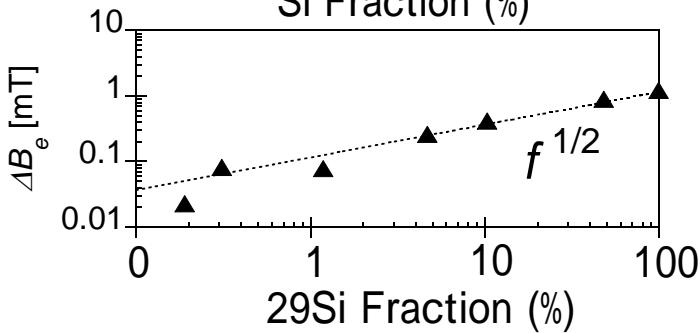
^{31}P ENDOR Line Broadening



ENDOR (Nuclear)

High $f > 0.1\%$
 \Rightarrow Linewidth $\sim f^{0.25}$ (blue line)
 Low $f < 0.1\%$
 \Rightarrow Linewidth $\sim f^{1.0}$ (green line)

$$f = {}^{29}\text{Si Fraction}/100$$



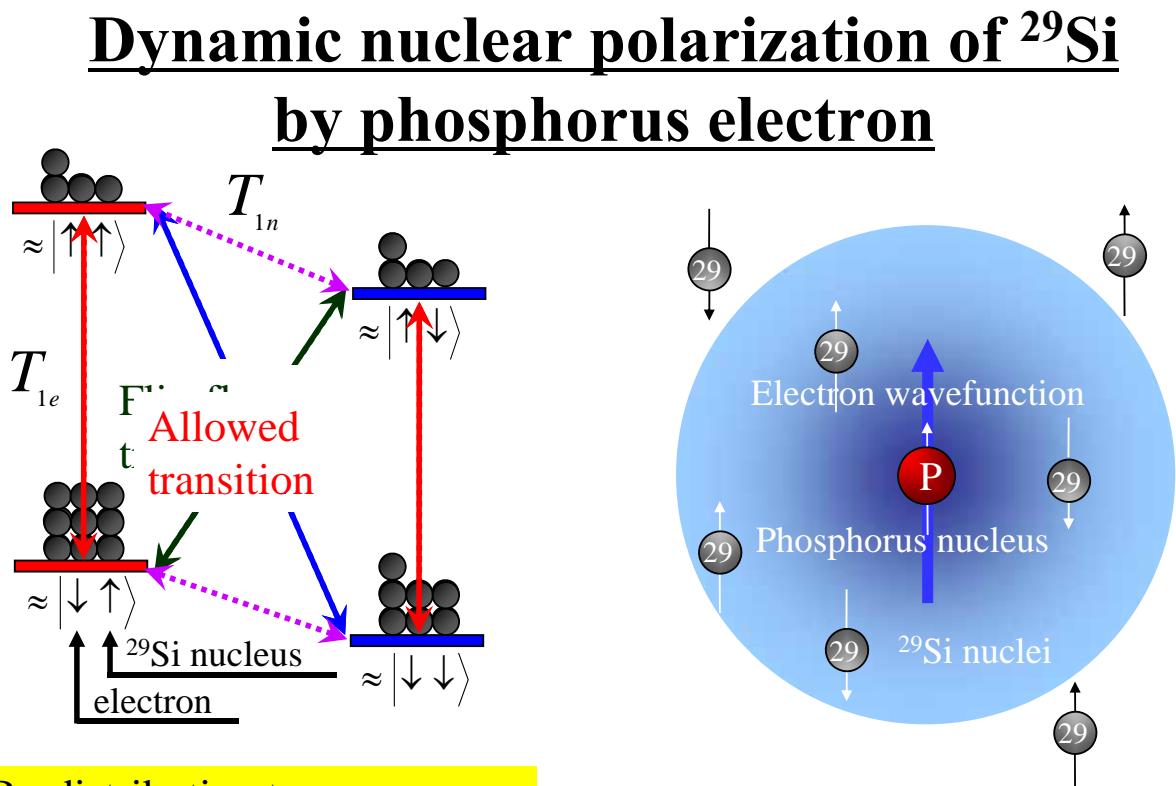
ESR (Electron)

$f > 0.1\%$
 \Rightarrow Linewidth $\sim f^{0.5}$

$$f = {}^{29}\text{Si Fraction}/100$$

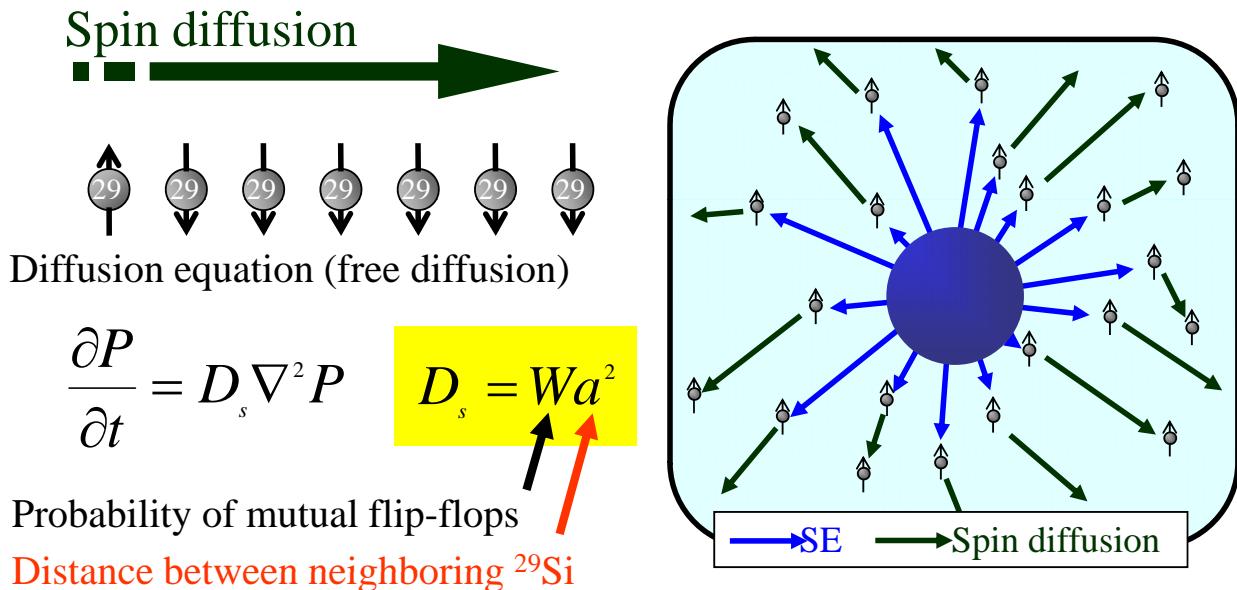
Phosphorus in silicon
Electron spin $T_2 > 0.3 \text{ sec at } 6K$
Nuclear spin $T_2 > 2 \text{ sec at } 6K$
in isotopically enriched ^{28}Si
(depleted of ^{29}Si nuclear spins)

A. M. Tyryshkin's talk



Saturation of allowed transition
leads to dynamic nuclear polarization

Spin Diffusion

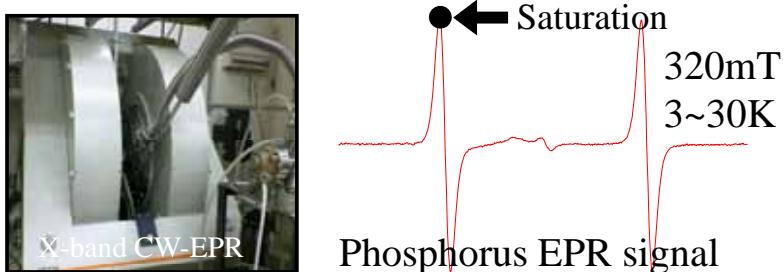


Diffusion coefficient is variable parameter with ^{29}Si concentration and can be investigated with isotopically controlled silicon

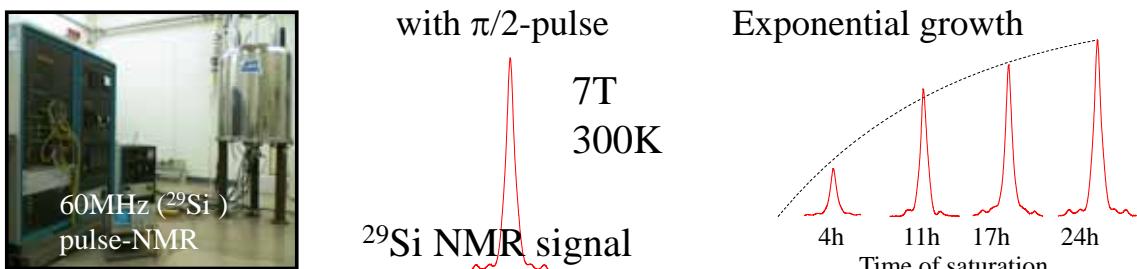
PRB (2008)

Experimental Method

1. Detect phosphorus EPR line and **saturate EPR transition** with high power microwave at **fixed magnetic field** and **fixed temperature**

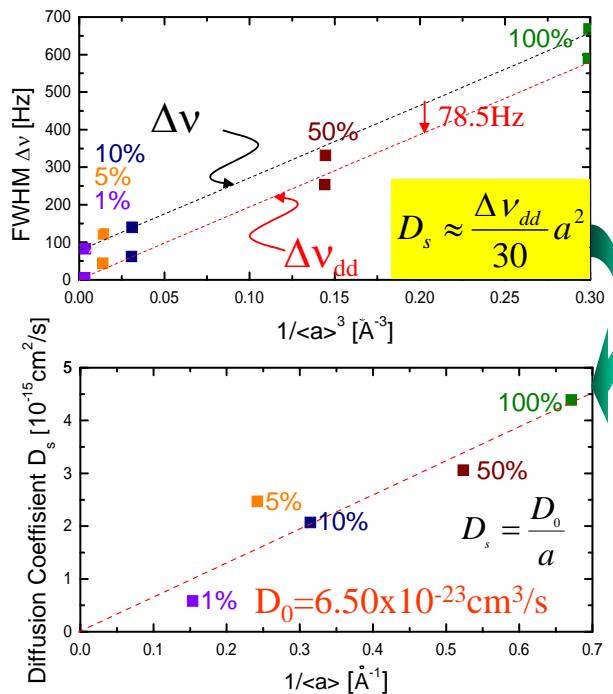
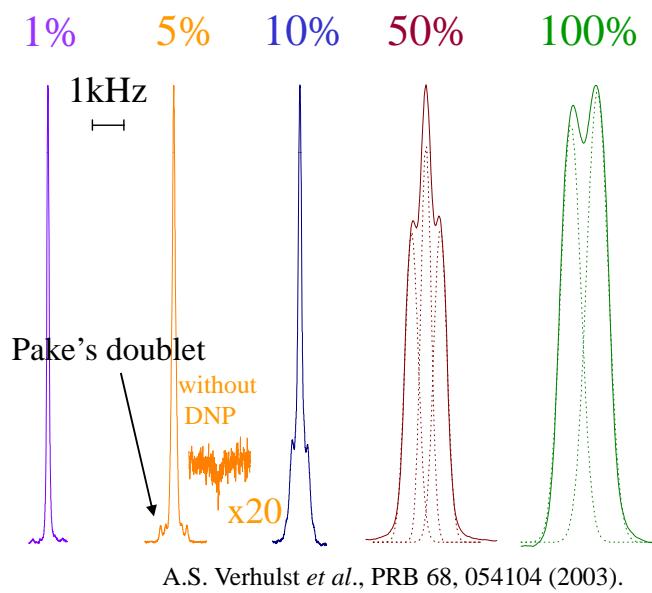


2. Transfer the sample to NMR spectrometer and obtain ^{29}Si NMR signal (E was estimated by comparison of **area** underneath absorption curve)



Spin Diffusion Coefficient

Enhanced ^{29}Si NMR signals in isotopically controlled silicon @7T, 300K



Spin diffusion coefficient was determined by the combination of dynamic polarization and host isotope effect on NMR linewidth

More details

^{29}Si nuclear polarization ~1.5%

H. Hayashi, K. M. Itoh, and L. S. Vlasenko, “Nuclear Magnetic Resonance Linewidth and Spin Diffusion in ^{29}Si Isotopically Controlled Silicon,” Phys. Rev. B, **78**, 153201 (2008)

H. Hayashi, K. M. Itoh, and L. S. Vlasenko, “Dynamic Nuclear Polarization of ^{29}Si Nuclei in Isotopically Controlled Phosphorus Doped Silicon,” Phys. Rev. B, **80**, 045201 (2009)